Simulation of Partial Discharge in High Voltage Power Equipment

A thesis submitted in partial fulfillment of the requirements for the award of the degree of

Master of Technology

in

Power Control and Drives

by

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June-2011

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CERTIFICATE

This is to certify that the thesis entitled, **"Simulation of Partial Discharge in High Voltage Power Equipment"** submitted by **Ms. Asima Sabat** in partial fulfillment of the requirements for the award of Master of Technology Degree in Electrical Engineering with specialization in **"Power Control and Drives"** at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by her under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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ABSTRACT

In high voltage (HV) electrical power system, variety of materials (solid, liquid and gaseous) is used for insulation purpose to protect the incipient failure in HV power equipment. Most of insulating materials are not perfect in all respect and contains always some impurities. The presence of air bubble is one of such impurities in insulating materials and highly undesirable for such type of insulation which causes a local weak zone inside the insulator. Insulation of the HV power equipment gradually degrades inside the insulator due to cumulative effect of electrical, chemical and thermal stress. Due to the high voltage stress the weak zone inside the insulator causes the partial discharge (PD) and finally the insulation properties of such materials is enormously degrades its quality. In this work, an electrical circuit model of void presence inside the solid is used to study the PD activity inside the insulator. A small cylindrical void is taken as impurity inside the solid insulating materials and placed at the middle of this insulator which is kept under uniform electric field using the plane-plane electrode arrangement. In this study an efforts have been made to investigate the maximum PD magnitude, number of PDs and other PD related parameters like PD distribution, frequency content of obtained PD pulse by using phase resolve partial discharge (PRPD) measurement technique. The entire simulation has been done with the MATLAB environment. The entire simulation has been done with the MATLAB environment. In addition, the relationship between the induced charge and void parameter is discussed for cylindrical void.

LIST OF ABBREVIATIONS

IEC standard	International Electro Techno Commission
PD	Partial Discharge
HV	High Voltage
MI	Measuring Instrument
CT	Current Transformer
PT	Potential Transformer
PRPD	Phase Resolved Partial Discharge
ORMPD	Online Remote Monitoring Of Partial Discharge
ICT	Information and Communication Technology
EMI	Electromagnetic Interference
DGA	Dissolve Gas Analysis
HPLC	High Performance Liquid Chromatography

LIST OF SYMBOLS

Symbols	Symbols Name
r	Radius of cylindrical void
d	Space between the electrodes
h	Height of cylindrical void
ε_0	Permittivity of free space
ε_r	Relative permittivity of dielectric (epoxide resin sample)
p	Atmospheric pressure
B	Constant characteristics of gas
E_i	Inception voltage
E_l	Limiting field for ionization
Δ z	Reciprocal of gap distance between electrodes
V	Volume of cylindrical void
Q	Apparent charge
V_s	High voltage supply
Z	Filter
Z_m	Input impedance
C_k	Coupling capacitor
C_t	Capacitance of test object
C_c	Capacitance of cylindrical void
C_b	capacitance of the remaining series insulation with void (C_c)
C_a	capacitance of the remaining discharge-free insulation of the rest of the solid insulator
V_a	Voltage across C_a
V_c	Voltage across the cylindrical void
R_m	Resistance of measuring system
L	Inductance of measuring system
C	Capacitance of measuring system

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CHAPTER-1

INTRODUCTION

Introduction

Literature review

Motivation and objective of the Thesis

Organization of the Thesis

Chapter-1

INTRODUCTION

1.1. INTRODUCTION

The quality of insulation plays an important role in high voltage (HV) power equipment. Different types of materials like solid, gaseous, liquid and combination of those materials are used for insulation purpose in high voltage power equipment. The insulation gradually degrades due to the cumulative effects of electrical, chemical and mechanical stresses caused by the partial discharges (PDs). The insulation of equipment is sensitive zone .Most of insulators are not in pure form, contains some impurity. Due to the presence of air impurity bubbles (void) are formed within the insulating material. It weakens the insulation region and responsible for appearance of PDs. The insulation of equipment is monitored, designed and safely handled by power engineer time to time. The insulation failure arises due to presence of PDs in high voltage power equipment. Partial discharges are always originated at void, poor conductor profiles in high voltage (HV) equipments. Because of the above reason PD detection and measurement is necessary for prediction of equipment from insulation damage and to assure a long-term operation of HV power equipment.

1.2 LITERATURE REVIEW

At the very beginning of the last century, when the high voltage technology was introduced for electrical power generation and transmission systems, partial discharges have already been recognized as a harmful source for the insulation ageing in the high voltage power apparatus [1-7]. Throughout the decades different techniques are developed for detection, measurement and behavior study of PDs inside the insulation model. Many authors are presented their work about the detection and measurement of PD as well as study the characteristic of PDs [1-27]. Author Van Brunt has presented his work on the role of memory effects in the PD behavior in 1994 [2]. Paithankar and Mokashi have proposed a defect identification technique based on chaos mathematics in 1997 [4]. Authors Nikolay Kolev, Peter Darjanova, Elissareta

Gadjev, Denitza Darjanova highlighted their work in 1997 and found out some important parameter (i.e., radius, height, volume of the void) relations which are responsible of occurrence of PD [7]. According to authors, PD phenomenon is a chaotic process. This means that PD is a nonlinear dynamical system. According to the authors Nikolay Kolev, Peter Darjanova, Elissareta Gadjeva, Denitza Darjanova, PD measurement method is the important test method for protecting the high voltage equipment from insulation damage and presence of PD is the main cause for degradation of insulation dielectric. They are highlighted their work in 1998 by developing a micro model for PD simulation which is based on mixed mode simulation using general purpose analysis programs such as PSPICE [5]. An another physical model has been developed in 2004 in which authors C. Y. Ren, Y. H. Cheng, P. Yan, Y. H. Sun, T. Shao highlighted their work on the characteristic study of epoxy resin sample enclosing a single and double void. They proposed their model by using SIMULINK [6]. In that work a physical model has been developed and its simulation circuit has built according to that model. Whole the arrangement is done for measurement of PDs by using SIMULINK. The insulation sample used for this model is epoxy resin for both single and double void. Author explains the characteristics of PD by highlighting the observed wave form of current impulse and voltage impulse in dime domain and also calculated the pulse width of that impulse in terms of nanosecond [6].

Some literature says the detection and measurement of the partial discharge on the basis of on-line measurement of partial discharge. This work has been presented by authors S. Karmakar et. al. in 2009[11-12]. Authors presented their work, on on-line monitoring of partial discharges in a model transformer and phase resolve partial discharge (PRPD) analysis using commercially available software named as ‘PDGold” for reorganization of the φ-q-n pattern. Author has also developed a continuous online PD monitoring system which is operated from remote place with the help of Information and Communication Technology (ICT) facilities using Lab VIEW software call as ICT enabled on line remote monitoring of partial discharge (ORMPD). In a modern high voltage power system, PD detection is used to monitor the state of health of high voltage power equipment in service and helps plant managers schedule device maintenance.

1.3. MOTIVATION AND OBJECTIVE OF THE THESIS

The appearance of PDs is a problem for insulation failure of high voltage equipment used in power plants. As the insulation of equipment is a sensitive zone therefore quality of insulation plays an important role in high voltage (HV) power equipment. It is found that most of the insulators are manufactured without avoided a small amount of impurity inside the insulator. The impurity of such insulating material is in the form of solid, gas or liquid. During the manufacturing process it is found that most of the solid insulation has impurity in the form of air bubbles (void) which creates a small weak zone inside the insulator. It weakens the insulation region and responsible for appearance of PDs with application of the high voltage. The insulation of equipment is monitored, cared, designed and safely handled by power engineer at the time of manufacturing. In high voltage power equipments, the insulation failure takes place is due to presence of PDs inside the void enclosed sample. Because of the above reason PD detection and measurement is necessary for prediction and reliable operation and increase the life time of insulation for HV power equipment.

The main objective of the thesis is

- To find out relationship between the void parameters (i.e. void size depend upon height, radius of void, volume of the void, apparent charge) which are the causes of appearance of PDs activities.
- To find out the PD activity inside the void enclosed with the solid insulation using MATLAB based SIMULINK model.
- To find out the
    - maximum PD magnitude variation with different applied voltage
    - number of PDs and other PD related parameters like PD distribution
    - frequency content of obtained PD pulse
- To find out the early detection of PD activity inside the solid insulation in high voltage power equipment.

1.4 ORGANISATION OF THESIS

This thesis is organized into five different chapters including introduction.

Chapter 1: In this chapter includes the introduction, motivation & objective of the project. It also covers the literature review on partial discharge characteristics as well as organization of the Thesis.

Chapter 2: This chapter describes basic concepts on partial discharge i.e. the necessity and detection of partial discharge in high voltage power equipment, its classification, various types of detection methods, factors affecting the insulation system, role of apparent charge for PD measurement.

Chapter 3: This chapter discussed about the mathematical modeling of partial discharge inside solid insulation. It includes cylindrical void model presence in the solid insulation and its equivalent circuit model for measurement of partial discharge. Also describes developed the MATLAB/SIMULINK model for partial discharge measurement.

Chapter 4: In this chapter simulation result of PD and analysis of the developed SIMULINK model has been discussed. It covers detection of PD signals, frequency content of obtained PD pulse, rise time, fall time calculation of PD pulse, number of PDs and other PD related parameters like PD distribution, maximum amplitude variation for different applied voltage, characteristics study on changing height and radius of void.

Chapter 5: Finally, in this chapter includes conclusion of the thesis work, scope of future work and references.

CHAPTER-2

BASIC CONCEPT OF PARTIAL DISCHARGE (PD)

Partial discharge (PD)

Necessity of detection of partial discharge

Classification of partial discharge

Effect of partial discharge in insulating system

PD detection methods

Factors influencing the dielectric strength of insulating material

Role of apparent charge for PD measurement

Chapter-2

Basic concept of Partial Discharge (PD)

2.1 PARTIAL DISCHARGE

According to IEC (International Electrotechnical Commission) Standard 60270, *Partial discharge is a localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor* [13]. In general partial discharges are a consequence of local electrical stress concentrations in insulation or on the surface of insulation. Such electrical discharges are appeared as impulses i.e., various forms of voltage impulse and current impulse having duration of much less than 1sec [13]. PD activity usually observed in high voltage power equipment like transformer, cable, bushings etc.

2.2 NECESSITY OF DETECTION OF PARTIAL DISCHARGE (PD)

Most of insulators are in impure form. Due to presence of air impurity bubbles (void) are created within the insulating material. It weakens the insulation region and responsible for appearance of PDs. The reason behind it is, the dielectric constant of the void is less than of its surroundings. So it causes insulation failure in high voltage equipments. Partial discharges are always occurs at void, bad conductor profiles in HV equipments. Though such discharge has less magnitude but it is responsible for degradation. Due to occurrence of discharge ultimately failure occurs in the insulation system. Because of the above reason PD detection and measurement is necessary for prediction of insulation life for HV power equipments.

PD usually starts within the voids or void enclosed within a solid dielectric. Void is the main source or main cause for appearance of PDs. Such discharges only partially bridges the distance between the electrodes. PD can also appear along the surface of different insulating materials. Appearance of partial discharges within an insulation material is usually initiated within gas-filled voids within the dielectric. The reason behind it is, the dielectric stress of the void is considerably less than the dielectric stress of its surrounding. Due to this reason the electric stress across the void is more than across an equivalent distance of dielectric. It is studied that if the voltage stress across the void exceeds the inception voltage of the gas within the void, then PD activity will take place. PD activity can also appear along the surface of solid insulating materials if the surface electric field is high enough to cause a breakdown along the insulator surface.

2.3. CLASSIFICATION OF PARTIAL DISCHARGE

Partial discharge phenomenon is divided into two types

(a) EXTERNAL PARTIAL DISCHARGE

External partial discharge takes place outside of the power equipments .Such types of discharges occur in overhead lines, on armature etc.

(b) INTERNAL PARTIAL DISCHARGE

The partial discharge which is occurring inside of a system .The discharge in void is belonging to such type of partial discharge and necessary for PD measurement system .PD measurement system gives the information about the properties of insulating material used in high voltage power equipments.

Different methods are employed for measurements of PDs. The principle behind for measurement of PD is generation/dissipation of energy associated with electrical discharges i.e. generation of electromagnetic waves, dissipation of heat energy, light and formation of noise etc. PD phenomena include several types of discharge which is surface discharge, cavity discharge, corona discharge, Treeing channel [2, 13].

(i) *Corona discharge:* Corona discharge takes place due to non uniformity of electric field on sharp edges of conductor subjected to high voltage. The insulation supplied for such type of discharge is gas or air or liquid [2]. Such type of discharges appears for a long duration around the bare conductor. They are not attacking directly to the insulation system like internal and surface discharge. Only by the indirect action of ozone formed by corona deteriorates insulating materials used.

(ii) *Surface discharge:* Surface discharges takes place on interfaces of dielectric material such as gas/solid interface as gets over stressed times the stress on the solid material.

This may occur in bushing, end of cable, any point on insulator surface between electrodes (high voltage terminal & ground). The occurrence of such discharge depends on various factors such as

- ✓ Permittivity of the dielectric material used
- ✓ Voltage distribution between the conductors
- ✓ Properties of the insulating medium where PD occurs

(iii) *Treeing channel:* High intensity fields are produced in an insulating material at its sharp edges and it deteriorates the insulating material .That is responsible for production of continuous partial discharge, called as Treeing channel.

(iv) *Cavity discharge:* The cavities are generally formed in solid or liquid insulating materials. The cavity is generally filled with gas or air. When the gas in the cavity is over stressed such discharges are taking place.

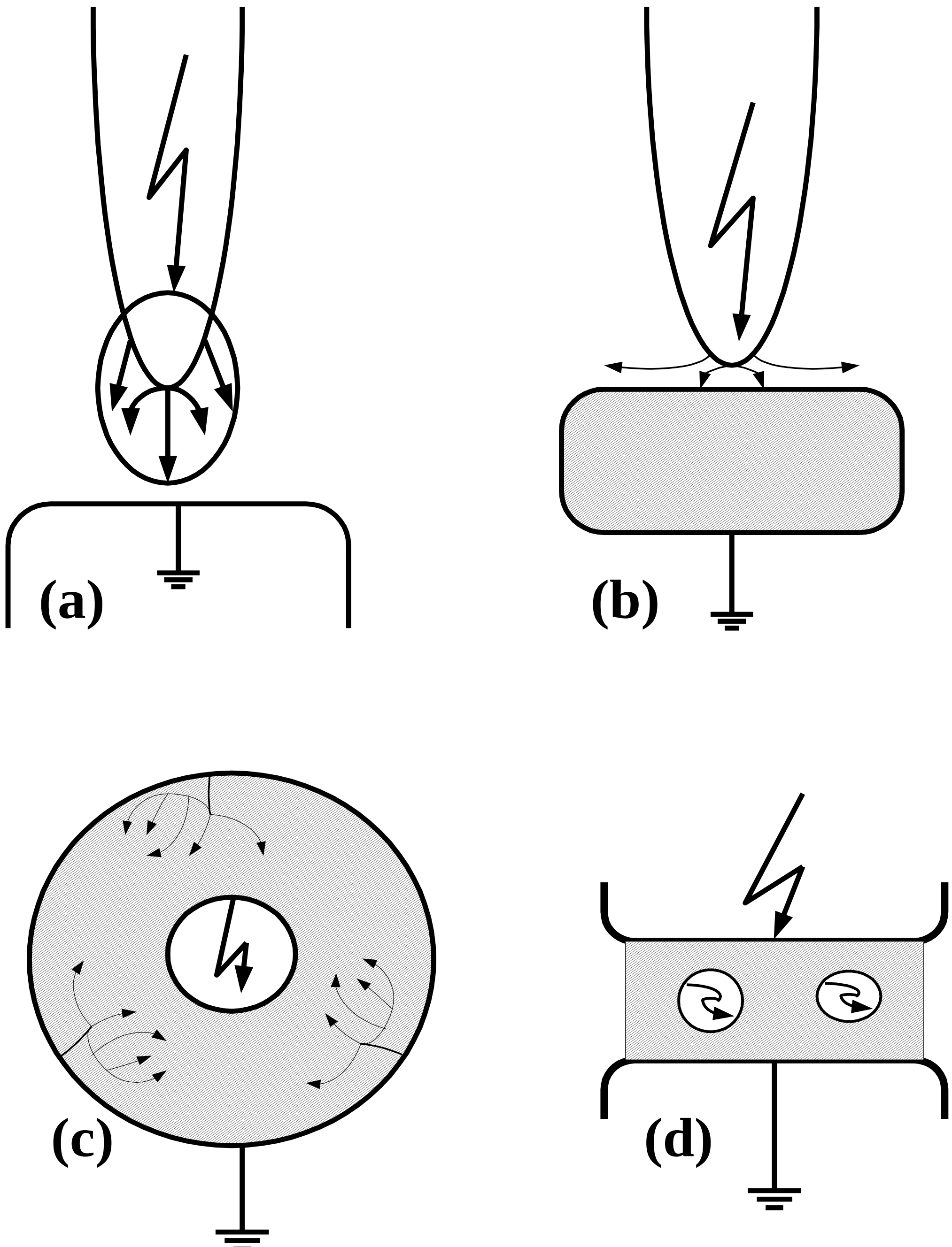

Figure 2.1. Various types of partial discharge occurs in the insulator (a) Corona or gas discharge, (b) Surface discharge, (c) Treeing channel and (d) Cavity discharge

2.4. EFFECT OF A PARTIAL DISCHARGE IN INSULATING SYSTEM

Appearance of PD is the main reason for degradation of insulating material and responsible for happening of electrical breakdown. The occurrence of repetition rate of discharge is the reason for mechanical and chemical degradation of the insulating material. The effect of discharge on high voltage power equipment is severe to the insulation system. Insulation damage happens due to appearance of partial discharge (PD). The conductivity property of the insulating material rises due to chemical changes in the dielectric. Dielectrics are classified into several types like inorganic dielectric and organic dielectric. Generally immunity of inorganic dielectrics is more. Porcelain, glass, mica are belonging to such dielectric. Polymer dielectrics are belonging to organic dielectrics.

Generally, PD generates energy in the form of heat. Heat energy is the main reason for degradation of the insulation. This effect is known as thermal effect on insulating materials used. For high voltage power equipments, the deterioration of the insulation can be known by monitoring the PD activities. PD activity should be monitored time to time by the power engineer or power manager at the time of manufacturing.

PD can be prevented through careful design and by selecting proper insulating material. So it's prevention and detection are essential for a secure, long-period of operation of high voltage equipments.

2.5. PD DETECTION METHODS

There are various methods are explored for the PD measurement based on both electrical and non electrical phenomena. The methods which have been popularly known for measurement of PDs are,

(i) Optical detection method
(ii) Acoustic detection method
(iii) Chemical detection method
(iv) Electrical detection method

2.4.1. OPTICAL DETECTION METHOD

In optical detection method light is dissipated in the form of ionization, excitation process during the appearance of discharge. The emission of light is dependent on the insulating medium used and other parameters like temperature, pressure. Transparent type of insulating material is applicable for this detection method. So some difficulty arises in case of implementation in high voltage transformers due to opaque nature of mineral oil.

2.4.2. ACOUSTIC DETECTION METHOD

In acoustic detection method, acoustic sensors are placed outside of the high voltage equipment for detection of PDs [10, 11]. The acoustic method is effective for perceiving and encoding the acoustic Signal generated during a partial discharge event. Acoustic methods have many advantages over other methods. Acoustic method is unaffected to electromagnetic interference (EMI), which can reduce the sensitivity of electrical methods [11]. The limitation of this detection method is the nature of acoustic wave propagation is complicated due to the use of non-homogeneous device like high voltage transformer. This method is widely applicable for detection of the various types of PD, finding the location of insulation failure. The difficulty arises behind this method is requirement of sensitivity.

2.4.3. CHEMICAL DETECTION METHOD

In the chemical detection method, PDs are detected by observing the chemical changes in the composition of insulating material used in HV power equipment. In this method, the dissolve gas analysis (DGA) and high performance liquid chromatography (HPLC) are extensively used for partial discharge diagnosis. DGA gives the information of partial discharge in terms of the volume of gas produced and HPLC measures the by products, such as glucose and degraded forms of glucose produced due to degradation of the insulation [10, 11]. Some drawback arises in this chemical detection method such as it does not give the information about the characteristics of PDs and location of PDs. It happens because of insolubility properties of glucose (in mineral oil) and degradation form of it is unstable in nature. Complicated instrumentation and its analysis process is required at the time of on-line monitoring of partial discharge activity.

2.4.4. ELECTRICAL DETECTION METHOD

Electrical detection method is one of the most popular methods in HV power equipment for partial discharge measurement. In this work, electrical detection method has been used to simulate the measurement of PDs in the model transformer. It focuses on appearance of the current and voltage pulse created by the current streamer in the void and impurities [10]. The pulses are less than one second and variation of frequency components in the range of KHz, The shape of the pulse and occurrence of phase location within the ac cycle gives the information about type of PD and information about insulation failure. Time domain recording device is used for observation of partial discharge impulses in this detection method. Various signal processing methods are applicable for identification/detection of PD signal. This method is also applicable for online electrical PD detection. Both broadband and narrow band electrical noises are found during the operation of HV power equipment. It is not easy to separate those electrical noises and PDs. The impulses which are received in this detection method depend on the geometry of high voltage transformer. This method has some drawbacks but has wide application in power plant which helps the power engineer and technician by giving necessary and important information regarding the characteristic, appearance of different types of partial discharge as well as about the occurrence of insulation failure in high voltage power equipment like transformer, cable etc.

2.6. FACTORS INFLUENCING THE DIELECTRIC STRENGTH OF INSULATING MATERIAL

The essential properties of the insulating materials used for high voltage power equipments are:

1. Insulation resistance should be high.
2. Dielectric strength should be high.
3. Should have good mechanical properties.
4. Materials should be unaffected by any other chemicals.

It has been studied that some factors or conditions make effect on dielectric strength of insulating materials. The dielectric strength of insulating material depends upon temperature, impurity, spacing between electrodes etc. and some other factors are also responsible for it.

A. TEMPERATURE

The function of the insulation is dependent on the operating temperature. Higher the temperature, the degree of degradation should be high and lesser will be its life. The temperature has an effect on the dielectric strength of insulating material. It depends upon the types of materials used in the high voltage power equipments. One example is coming for it is the effect of temperature in the dielectric strength of insulating material used in power equipments like dry type transformer .The used dielectric medium used is transformer oil which is insensitive to the temperature. As the oil has lower boiling point, the dielectric strength of the material used decreases due to creation of vapor bubbles. The temperature at which the power equipments operate is responsible for degradation of insulating material used. The characteristics of strength of the material used and temperature at which equipments operate is inversely proportional.

B. ELECTRODE AND GAP CONDITIONS

The breakdown strength of oil depends upon its width, electrode shape and material used for insulation. The size and shape of electrodes are responsible for determination of the volume of medium subjected to high electric stress. Increase in volume increases the impurity content particles. More impurity particles content lowers the breakdown voltage of the space between electrodes.

C. IMPURITIES

The presence of impurity will make an effect on insulating material which is used in power equipments. The strength of dielectric liquid used in high voltage transformer decreases to 70 % because of the impurity content like metal particles. Impurity includes solid particles like carbon, wax, cellulose fibre, acids. Impurity contents create imperfections in the insulation region.

D .OTHER FACTORS

The dielectric strength of insulating material which is used in power equipments is affected by other factors also i.e. thickness of the specimen and humidity. Thickness of the specimen is directly proportional to the dielectric strength of the insulating material and surface condition like humidity is inversely proportional to the dielectric strength of the material. It has been observed that

- Dielectric strength increases with the increase in thickness of the specimen.
- Dielectric strength decreases with the increase in humidity.

2.7. ROLE OF APPARENT CHARGE FOR PD MEASUREMENT

Partial discharge is the process of dielectric breakdown of a small portion of a solid or a liquid electrical insulation system which is under high voltage stress. Partial discharges within an insulation system may or may not reveal any visible discharges as the discharge events tend to have a more sporadic character. The effects of partial discharge within cables and other high voltage equipment should not be treated lightly as it can even lead to complete failure. Partial discharge is an electrical discharge that can potentially cause serious problems amongst high voltage equipment. As the partial discharge is not measurable directly with the help of the apparent charge method PDs are detected and measured in high voltage power equipment. The apparent charge is the important quantity of all PD measurement. The word apparent was introduced because this charge is not equal to the amount of charge locally involved at the site of discharge or void [13]. According to IEC standard 60270 (International electro techno Commission), the definition of Apparent charge is given by **"***Apparent charge q of a PD pulse is that unipolar charge which, if injected within a very short time between the terminals of the test object in a specified test circuit, would give the same reading on the measuring instrument as the PD current pulse itself. The apparent charge is usually expressed in picocoulombs*". The apparent charge cannot be measured directly. To measure apparent charge the measuring instrument requires some calibration. As the partial discharge is highly depends on the geometrical configuration of the void presence in the solid insulation. As the PD inside the power equipment is not directly measurable because of the PD sources are not accessible. To overcome the above problem an apparent charge method is used for measurement of the PD activity inside the solid insulation model.

CHAPTER-3

MATHEMATICAL MODELLING OF PARTIAL DISCHARGE INSIDE SOLID INSULATION

Selection of void parameter
Circuit model for PD measurement
Partial Discharge measurement system
Electrical circuit illustration for PD measurement
Simulink model description for detection for partial discharge

Chapter-3

Mathematical modeling of partial discharge inside solid insulation

3.1. SELECTION OF VOID PARAMETER

Void parameters are the most important factor for PD characteristics. PD characteristics also depend on types of void used. Requirement of parameters are height, diameter, and volume of void. According to the [7], parameters are chosen for finding out the relationship of void parameter with apparent charge. Gap spacing between the electrodes is taken 0.02 mt., height of the void varies from 0.002 - 0.008 mt. and radius of the void varies from 0.005-0.04 mt. The other parameters used for simulation is depicted in Table 1. All the dimensions are expressed in metre unit.

TABLE-I

PARAMETRS USED FOR SIMULATION

Sl. No.	Parameter	Symbol	Default value	Dimension
1	Gap spacing between electrodes	d	0.02	m
2	Relative permittivity of dielectric (for epoxide resin)	ε_r	3.5	
3	Permittivity of free space	ε_0	8.852×10^{-12}	F/m
4	Constant characteristics of gas	B	8.6	$Pa^{0.5}\ m^{0.5}$
5	Pressure	p	10^5	N/m^2

3.2. CIRCUIT MODEL FOR PD MEASUREMENT

The behaviour of internal discharges at AC voltage can be interpreted using the well known a-b-c model which is shown in Fig. 3.1. Different models are used for partial discharge phenomenon which is compared with experimental data .The Pedersen model is established to get better accuracy.

A. Circuit Model

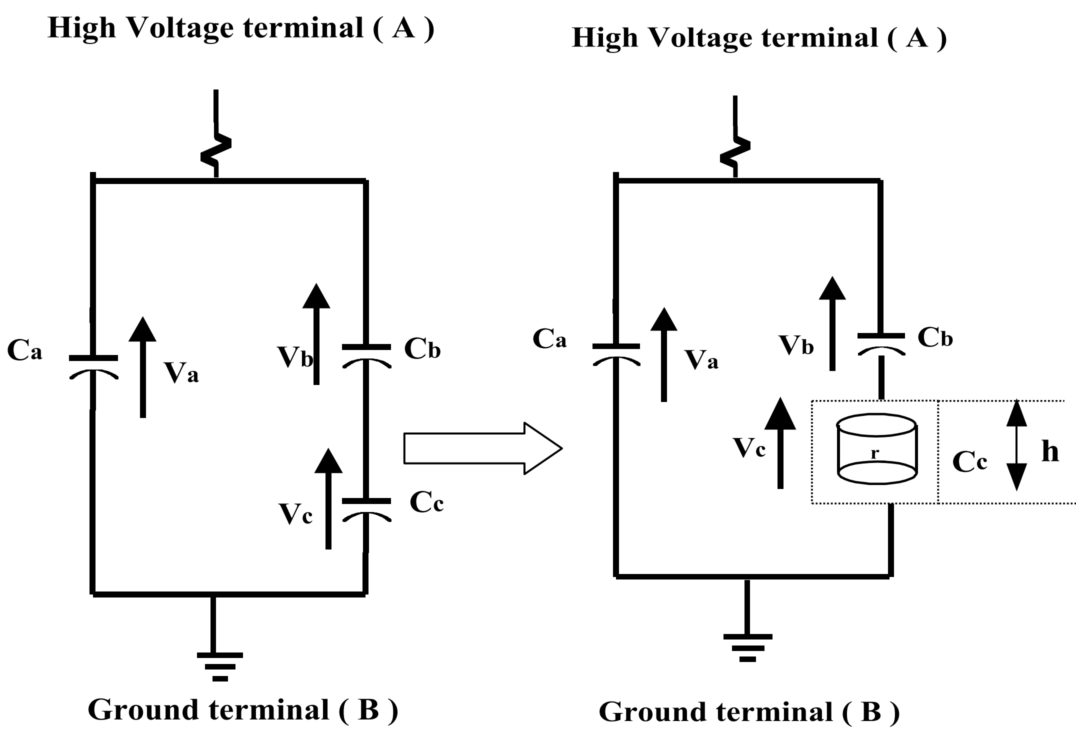

Figure 3.1. Cylindrical Void model inside solid dielectric

3.3. PARTIAL DISCHARGE MEASUREMENT SYSTEM

The basic components required for measurement of PD are t

- A coupling capacitor –Coupling capacitor should have low inductance. It holds up low level partial discharge at a particular applied voltage for measurement of discharge magnitude when coupling capacitor is connected in series with the measuring system. A higher level of partial discharge is measured when coupling capacitor and measuring system is connected separately. This happens when measuring system is connected in series with the test objet.

- A high voltage supply –High voltage supply is having low degree of background noise to pass the discharge magnitude which is to be measured for a particular applied voltage.
- High voltage connection having sufficiently lower degree of background noise.
- Input impedance for measuring system consisting of R_m, L, and C. Input impedance is the most determinant factor for the wave shape of the PD impulse.
- A high voltage filter- It is used for reduction of background noise from the power supply. Such filters are also used for improvement of voltage stability.
- A test object- Consists of three capacitors. One capacitor is connected in parallel with the two series capacitors

Test object →

- C_c corresponds to the cylindrical void present inside the solid insulation
- C_b corresponds to the capacitance of the remaining series insulation with void (C_c)
- C_a corresponds to the capacitance of the remaining discharge-free insulation of the rest of the solid insulator

- Measuring instrument -The measuring system is used to distinguish the observed electrical discharges from the test object.
- Display unit and PC software used for characteristic study and its analysis.

3.4. ELECTRICAL CIRCUIT FOR ILLUSTRATION OF PD MEASUREMENT

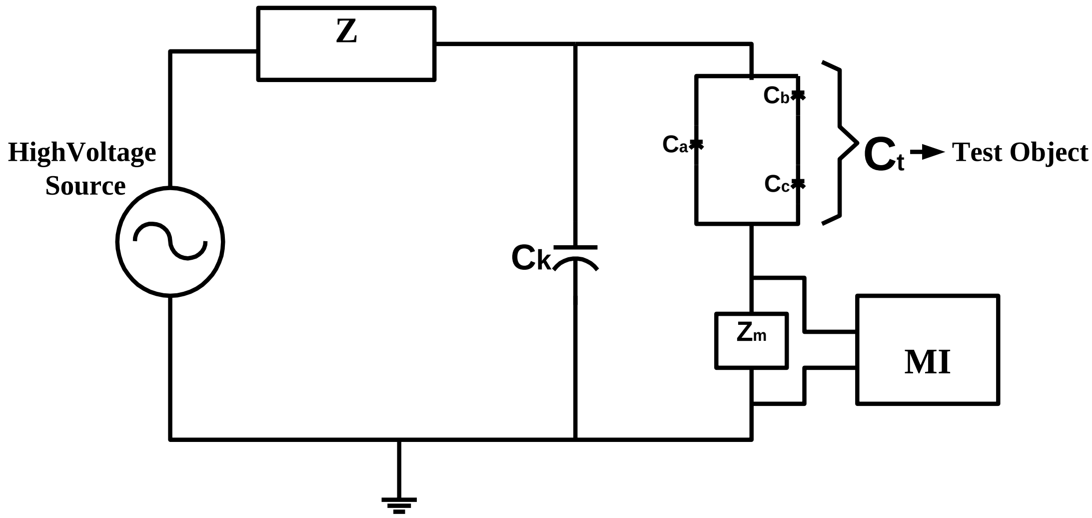

Figure 3.4. Electrical equivalent circuit model of cylindrical void in solid insulation along with high voltage equipment

In the equivalent circuit model the capacitance C_c corresponds to the cylindrical void present inside the solid insulation, C_b corresponds to the capacitance of the remaining series insulation with void (C_c) and C_a corresponds to the capacitance of the remaining discharge-free insulation of the rest of the solid insulator. Such circuit is energized with ac voltage source, a recurrent discharge occurs. Capacitance of the void C_c is charged which is responsible for occurrence of break down.

Voltage across the cylindrical void C_c is given by

$$V_c = V_a \times C_b / (C_a + C_b) \qquad \text{.................... (3.1)}$$

Apparent charge which is measurable at the high voltage terminal A and ground terminal B can be calculated from [3]

$$Q = C_b \times V_c \qquad \text{....................... (3.2)}$$

Pedersen has suggested a model [3] which is based on induced charge. According to this model, apparent charge will be given by [1] for cylindrical void

$$Q = S \times V \times \varepsilon_0 \times \varepsilon_r \times (E_i - E_l) \times \Delta z \qquad \text{......................} (3.3)$$

where, S is void geometric factor, V is volume of cylindrical void and is given by $\pi r^2 h$, (where, r = radius of void, h = height of void), ε_0 is permittivity of free space, ε_r is relative permittivity of dielectric, E_i is inception voltage for streamer inception, E_l is limiting field for ionization and Δ z is reciprocal of distance between two electrodes is (1/d).

The value of (E_i-E_l) can be calculated by equation [3.1, 3.5]

$$\frac{E_i}{p} = \frac{E_l}{p}.\left(1 + \frac{B}{\sqrt{2ap}}\right) \qquad \text{......................} (3.4)$$

where, B is constant characteristic of gas in void, a is radius of void, p is pressure of gas in void, of gas in void,

$$E_l/p \text{ (for air)} = 24.2/\text{pa.m.} \qquad \text{.........................} (3.5)$$

Apparent charge is calculated by using above parameter values by putting in this Eqn. 3.3. It has been studied that, PD phenomena is investigated from different electrical model. This present work consists of a cylindrical void model placed inside an epoxide resin sample which is intended to use in universal software for both electrical and electronics circuit analysis of MATLAB type. A SIMULINK model has been developed to study the discharge characteristic in a single void which is shown in Fig. 3.1.

3.5. SIMULINK MODEL DESCRIPTIONS FOR DETECTION OF PARTIAL DISCHARGE

Partial discharges are electrical discharges confined to a localized region of the insulating medium in high voltage (HV) power equipment. The PD phenomenon usually commences within the void, cracks, in bubbles within liquid dielectrics or inclusion within the solid insulating medium. In addition, PDs also occur at the boundaries between the different insulating materials, contamination, poor conductor profiles and floating metal-work in the HV equipment

[3-8]. The electrical PD detection method are based on the appearance of the PD current or voltage pulse across the test object for fundamental investigation, which may be either a simple dielectric test object or large HV power apparatus. To evaluate the fundamental quantities of PD pulse, a simple equivalent capacitor circuit of solid insulator having cylindrical void is taken into consideration for this work.

TABLE -II

SPECIFICATION OF THE DIFFERENT COMPONENTS AND THEIR VALUE TAKEN FOR PARTIAL DISCHARGE SIMULATION

Sl. No.	Components	Value/ Rating
1	HV transformer	0.23/5 kV,50 kVA
2	HV measuring capacitor	200/1500pF
3	HV coupling capacitor	1000µF
4	Detector circuit resistance	50Ω
5	Detector circuit inductance	0.63mH
6	Detector circuit capacitance	0.47µF

In the equivalent circuit the capacitance C_c corresponds to the cylindrical void present inside the solid insulation, C_b corresponds to the capacitance of the remaining series insulation with void (C_c) and C_a corresponds to the capacitance of the remaining discharge-free insulation of the rest of the solid insulator. Generally, ($C_a >> C_b >> C_c$). According to the size of void in insulation sample (epoxide resin), a cylindrical void of height of 4 mm and a radius of 2 mm is used in a cube sample (30mm ×30mm ×5mm) in this model. The void is located in the centre of the insulation sample.

The capacitance value of sample is calculated by using the formula:

$$C_a = \frac{\varepsilon_0 \times \varepsilon_r \times (a-2b) \times b}{c} \quad \text{……………..} (3.6)$$

$$C_b = \frac{\varepsilon_0 \times \varepsilon_r \times r^2 \times \pi}{c-h} \quad \text{……………..} (3.7)$$

$$C_c = \frac{\varepsilon_0 \times r^2 \times \pi}{h} \quad \text{……………..} (3.8)$$

The applied voltage to the insulation sample is 5 kV and frequency of 50 Hz. The capacitance value of sample is calculated as $C_a = 4.83\times10^{-12}$ F, $C_b = 3.89\times10^{-13}$ F, $C_c = 2.78\times10^{-14}$ F. In this study the value of the void model and the other high voltage equipment for measurement of PD has been taken as per Table 1 and Table 2 respectively.

CHAPTER-4

SIMULATION RESULTS AND DISCUSSION

Chapter-4

Results and Discussions

4. RESULTS AND DISCUSSIONS

To observe the PD activity due to presence of cylindrical void inside the developed solid insulation model a high voltage of 0-30 kV is applied in between the electrode. As the occurrence of the PD inside the power equipment is not directly measurable because of the PD sources are not accessible an apparent charge method is used. According to IEC 60270 apparent charge '*q*' of a PD pulse is that charge which if injected in a short time between the terminals of a test object in a specified test circuit, would give the same reading on the measuring instruments as the PD current pulse itself.

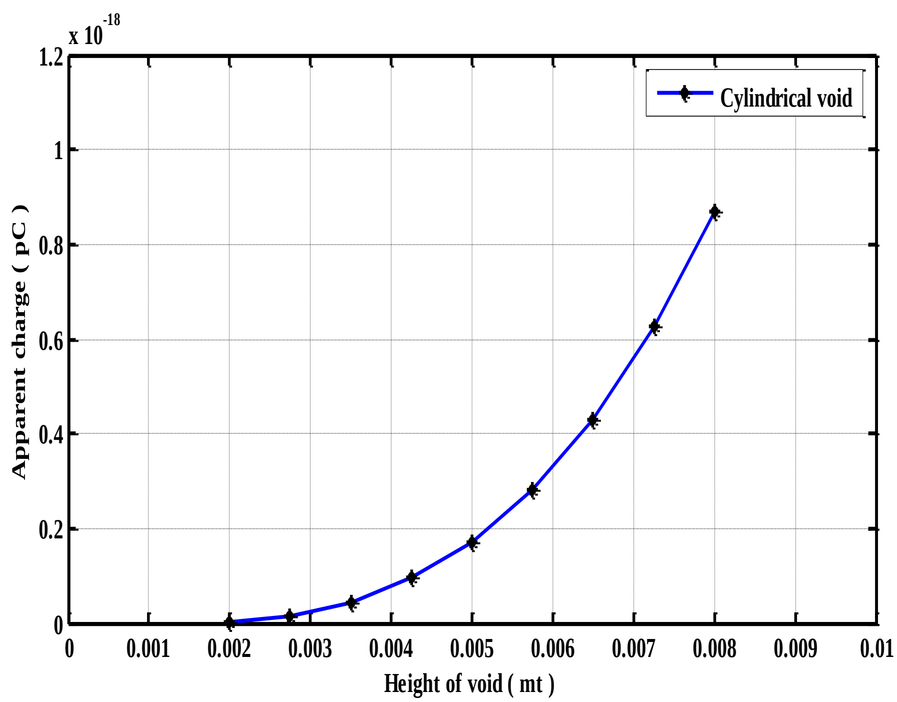

Figure 4.1.The relation between apparent charge and height of the void

It also studied that, apparent charge is an important factor for PD measurement in the high voltage power equipment. As the partial discharge is highly depends on the geometrical configuration of the void presence in the solid insulation the relation between apparent charge and height of the void, volume of the void and diameter of the void is considered in this study.

The relation between the apparent charge and the height of the cylindrical void is shown in Fig. 4.1. It is observed from the Fig. 4.1 that with increase of the cylindrical void height from 0.002 to 0.008 mt, the apparent charge will increase from 0.0034×10^{-18} to 0.8695×10^{-18} pC. It is observed from simulation result that the relation between height of void and apparent charge curve is a linear one.

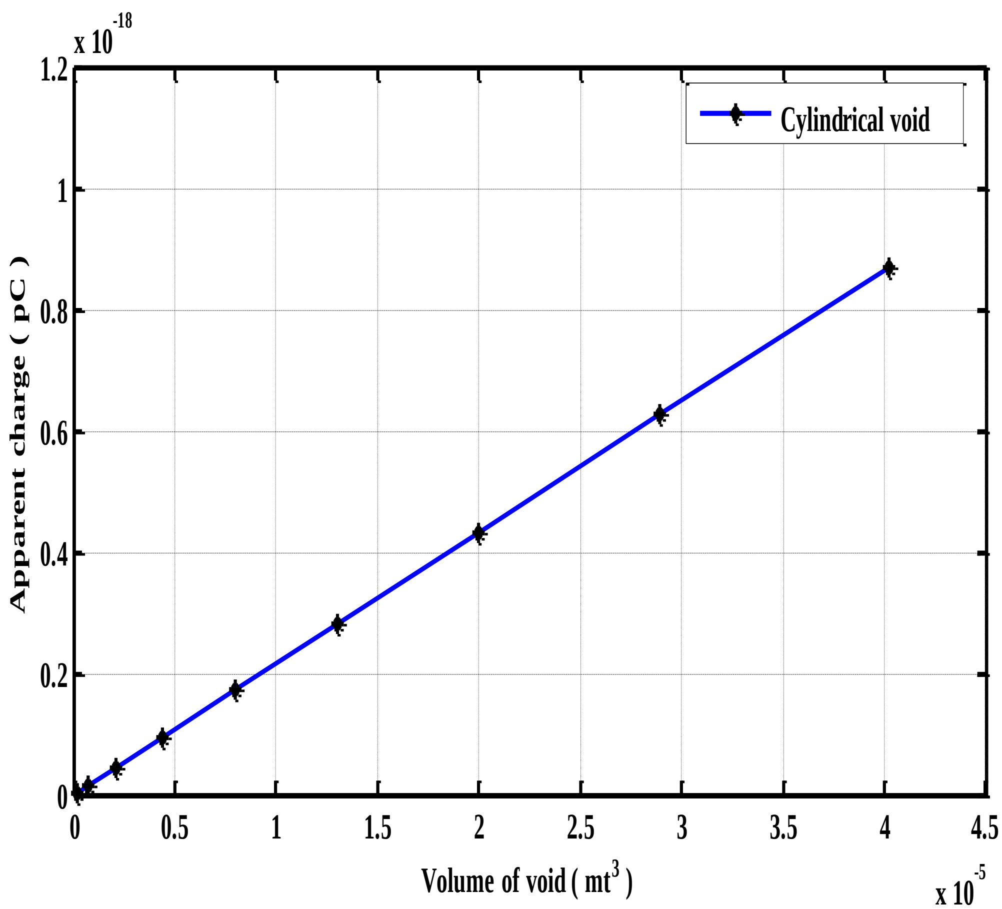

Figure 4.2**.** A linear relationship of volume of void with apparent charge

Another study has been made in this work which is the relation between the apparent charge and the volume of the void. It is observed that the apparent charge is also a function of volume geometry of the cylindrical void model. It is also observed that, the volume is directly related to apparent charge which is shown in Fig. 4.2. It is observed from simulation result that the relation between void volume and apparent charge curve is a linear one.

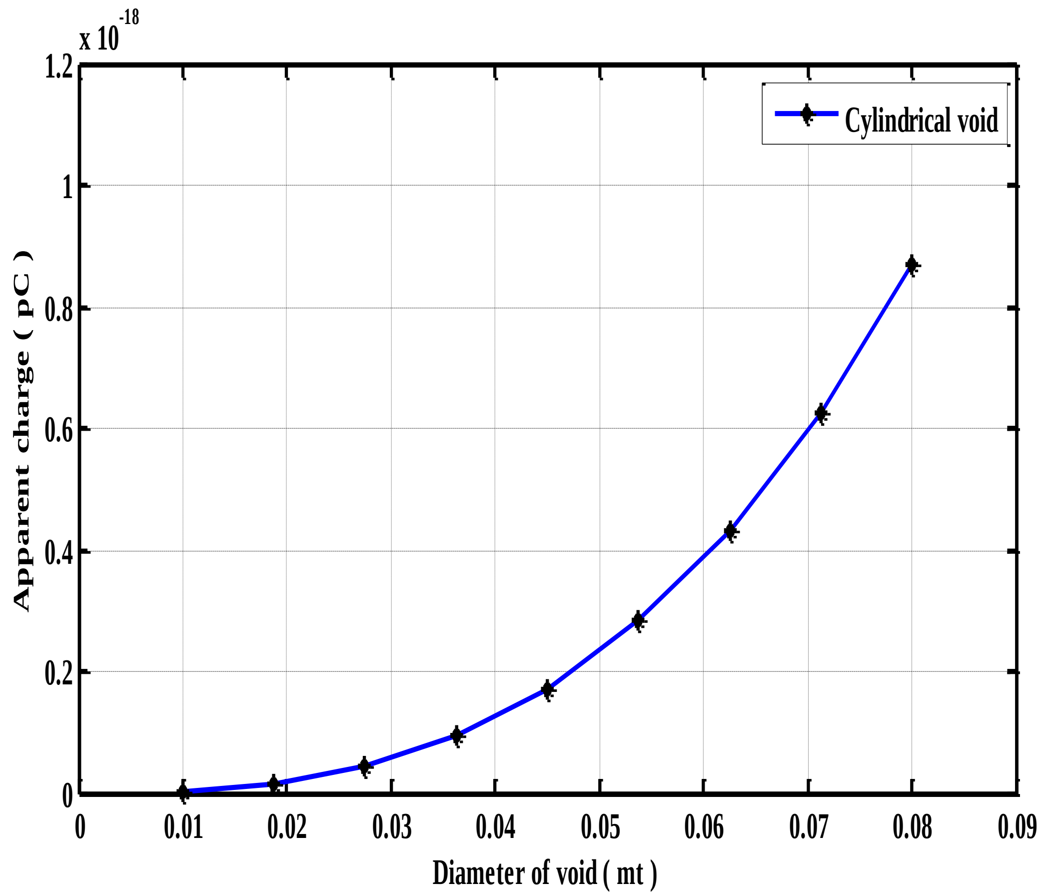

Figure 4.3.The relationship of diameter of void with apparent charge

To study the PD activity due to presence of cylindrical void inside the solid insulation, apparent charge and size of the void is also considered in this work. In Fig. 4.3 it is observed that with the increase of the diameter of the cylindrical void apparent charge is increase. It is observed from the Fig. 4.3 the diameter of the cylindrical void varies from 0.01 mt.-0.08 mt. and the corresponding value of the apparent charge is varies from 0.034×10^{-18} to 0.8695×10^{-18} pC.

It is understand from the above result that the magnitude of the PD is also vary as the apparent charge is varying with changing the void height, diameter and void volume.

In this work, the sample dimension is (30×30×5) mm and height of the void has taken less than 5 mm i.e., 4 mm and radius of the void has taken 2 mm. The void capacitances of the solid insulation are calculated by using Eqn. 3.6, 3.7 and 3.8. The amplitude of the PD pulse is changing with the size of the void which is shown in Fig. 4.4. The void capacitance is changes with the changing the radius of the void keeping the void height same which is depicted in the Table 3.

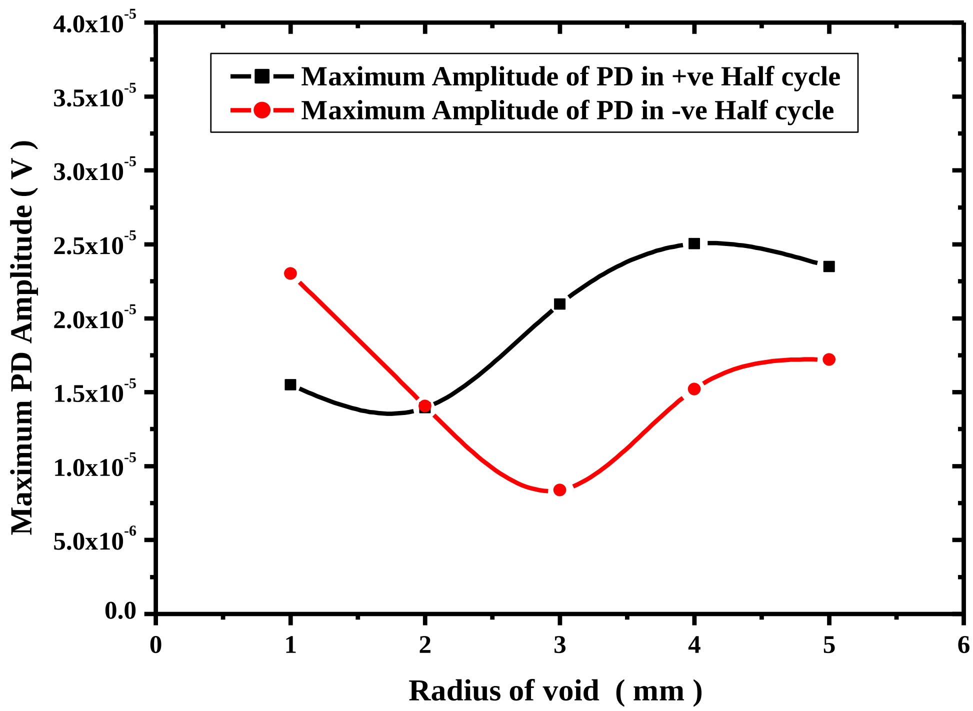

Figure 4.4. Variation of PD amplitude for different radius of void

TABLE-III

VARIATION OF PD AMPLITUDE FOR DIFFERENT RADIUS OF VOID

Height of void (mm)	**Radius of void (mm)**	**Sample dimension**	**C_a (Farad)**	**C_b (Farad)**	**C_c (Farad)**
4	1.00	30×30×5	5.2038×10^{-12}	9.7261×10^{-14}	6.9472×10^{-15}
4	2.00	30×30×5	4.8321×10^{-12}	3.690×10^{-13}	2.780×10^{-14}
4	3.00	30×30×5	4.4604×10^{-12}	8.7535×10^{-13}	6.2524×10^{-14}
4	4.00	30×30×5	4.0887×10^{-12}	1.5561×10^{-12}	1.1115×10^{-13}
4	5.00	30×30×5	3.717×10^{-12}	2.1431×10^{-12}	1.7368×10^{-13}

Similarly it is found that by changing the void height and keeping the void radius constant (2 mm) the amplitude of the PD pulse is also changes and it is shown in Fig. 4.5. It also proves that the dimensional configuration of void parameter affects the changes in the PD amplitude while 5 kV applied voltage is provided between the plate electrodes. The amplitude of the PD pulse are determine by the following equation

$$V = \frac{q}{C_a + C(1+\frac{C_a}{C_k})} \times (e^{-t/2Rm}) \times \cos(\omega t) \qquad (4.1)$$

where, V represents the value of PD amplitude, q for apparent charge, C_k for value of coupling capacitor, $w = \sqrt{\left(\frac{1}{Lm} - \frac{1}{4R^2m^2}\right)}$, $m = \frac{C_a \times C_k}{C_a + C_k} + c$. Therefore by increasing the height of the void the PD pulse amplitude is also increases as because of the apparent charge of the same void is changes. Due to the change of the void height the void capacitance is also changes which are depicted in Table 4.

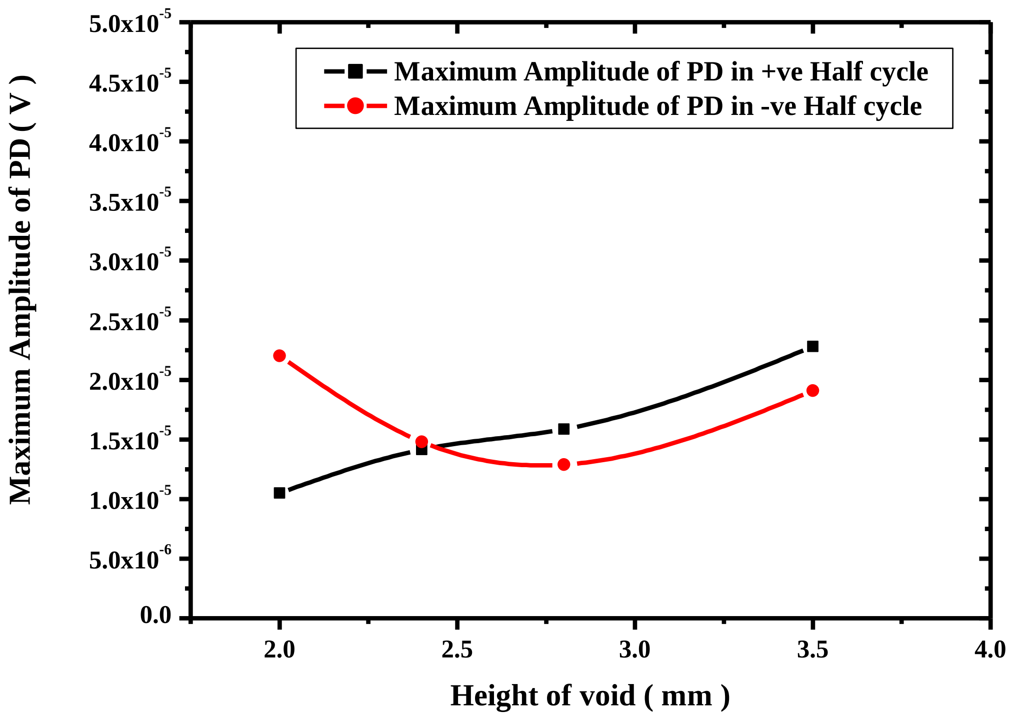

Figure 4.5. Variation of PD amplitude for different height of void

It has been studied that by increasing the height and radius of the void amplitude of PD pulse increases in positive half cycle and decreases in negative half cycle. It is found that by changing of height pulse amplitude increases linearly but in case of increase of radius, when the ratio of radius to height increases i.e., typically more than one, amplitude of PD pulse will decrease. As the height increases from 2 to 4 mm and taking constant radius is 2 mm, the pulse amplitude will vary. The ratio of radius to height is less than one so the amplitude in increasing which is shown in Fig. 4.5.

TABLE-IV

VARIATION OF PD AMPLITUDE FOR DIFFERENT HEIGHT OF VOID

Radius of void (mm)	Height of void (mm)	Sample dimension	C_a (Farad)	C_b (Farad)	C_c (Farad)
2	2.00	30×30×5	4.8321×10^{-12}	1.2968×10^{-13}	5.5578×10^{-14}
2	2.40	30×30×5	4.8321×10^{-12}	1.4963×10^{-13}	4.6315×10^{-14}
2	2.80	30×30×5	4.8321×10^{-12}	1.7683×10^{-13}	3.9698×10^{-14}
2	3.50	30×30×5	4.8321×10^{-12}	2.5936×10^{-13}	3.1758×10^{-14}
2	3.90	30×30×5	4.8321×10^{-12}	3.5367×10^{-13}	2.8501×10^{-14}

To simulate the PD activity inside the solid insulation medium a MATLAB Simulink model is considered in this work. An increasing voltage of 0-30 kV is applied between the void models to observe the PD activity inside the solid insulation. It is observed that with application of 0- 4 kV between the cylindrical void models no PD was found. The field intensity within the void not exceeds beyond the breakdown strength of gas in void below the applied voltage of 5 kV. Further with increase of high voltage between the test object PDs are appearing having small amplitude. At the applied voltage of 5 kV PDs are found due to presence of void inside the solid insulation. With the applied voltage of 5 kV the field intensity within the void exceeds the breakdown strength of gas in void and PD pulse is observed which is shown in Fig. 4.6.

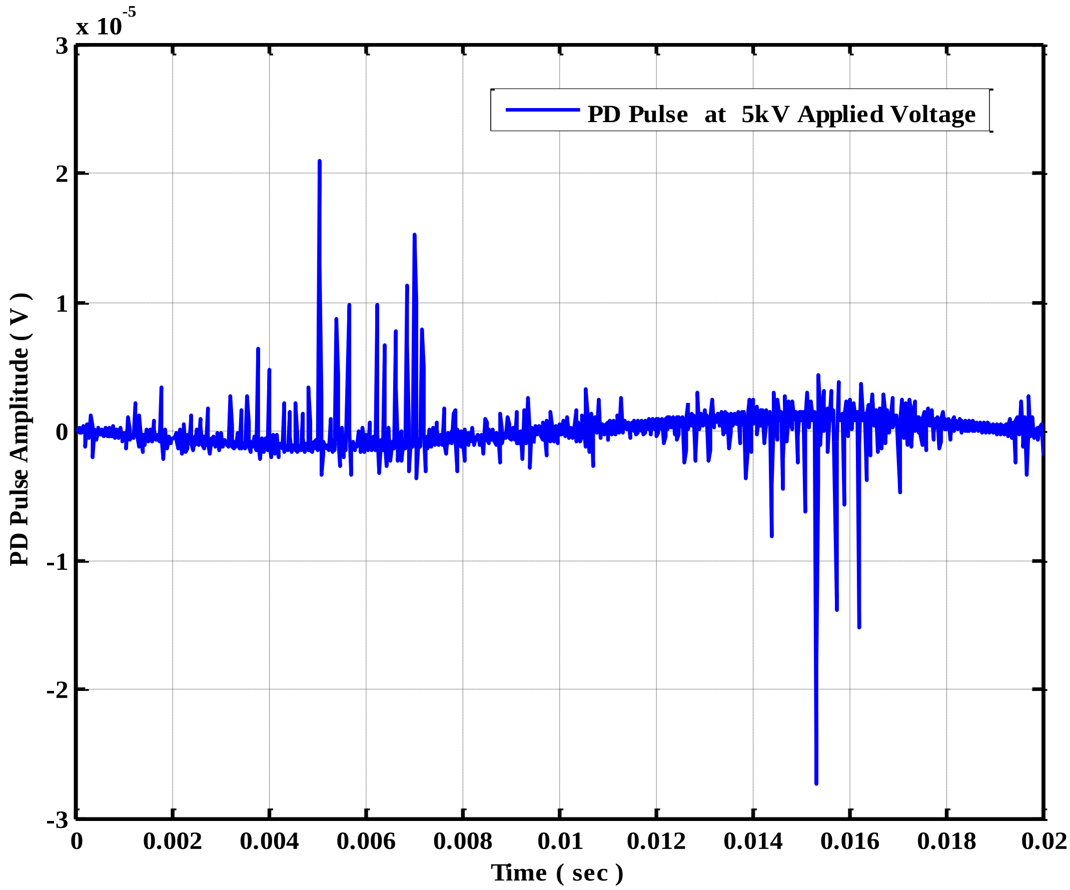

Figure 4.6. PD pulse observed with 5 kV applied voltage

To identify the position of PDs with respect to the phase angle, phase resolve partial discharge (PRPD) detection technique is an important tool for monitoring of HV power equipment. To distinguish the PDs with other discharges, the presence of PD pulses in the different quadrant gives the cause of occurrence of PDs [6-8]. The applied voltage of 5 kV and along with the PD pulse is shown in Fig. 4.7. It is observed that PD pulse is appears nearly 90 degree phase angle in positive half cycle and nearly 270 degree phase angle in negative half cycle of the 5 kV applied voltage which is shown in the Fig. 4.7. Due to lower rate of applied voltage between the test object is not enough to cause field intensity within the void in excess of PD inception strength.

Therefore, PDs are mostly appearing at 90 degree phase angle and 270 degree phase angle of the applied voltage where the maximum amplitude of the applied voltage is reached.

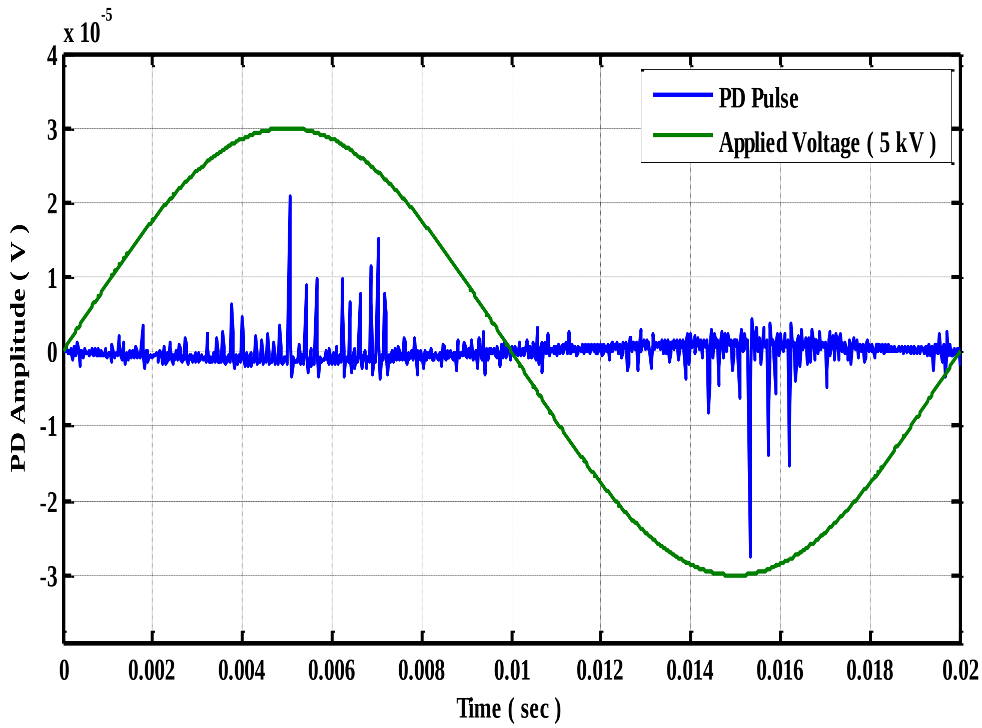

Figure 4.7. Observed PD pulse with 5 kV applied voltage between the test object

Further an analysis has been made for presence of PD pulses over a total measuring period under applied voltage of 5 kV. In this study the total phase angle is divided into eight section having 45˚ phase angle each. It is observed that, the number of PD pulse appeared in the each section is not constant as the PD is the random phenomenon. In this Fig. 4.8 the number of PD pulses is appeared in the different phase angle of the applied voltage. It is observed that with the application of the applied voltage of 5 kV, the observed PD signals contains seventy one (71) PD pulse out of which thirty nine (39) numbers of PD is appears in the positive half and thirty two (32) numbers of PD pulse are appeared in the negative half of the applied voltage. In addition, it is also observed that the number of the PD appears in different applied voltage is not fixed rather it is appears randomly.

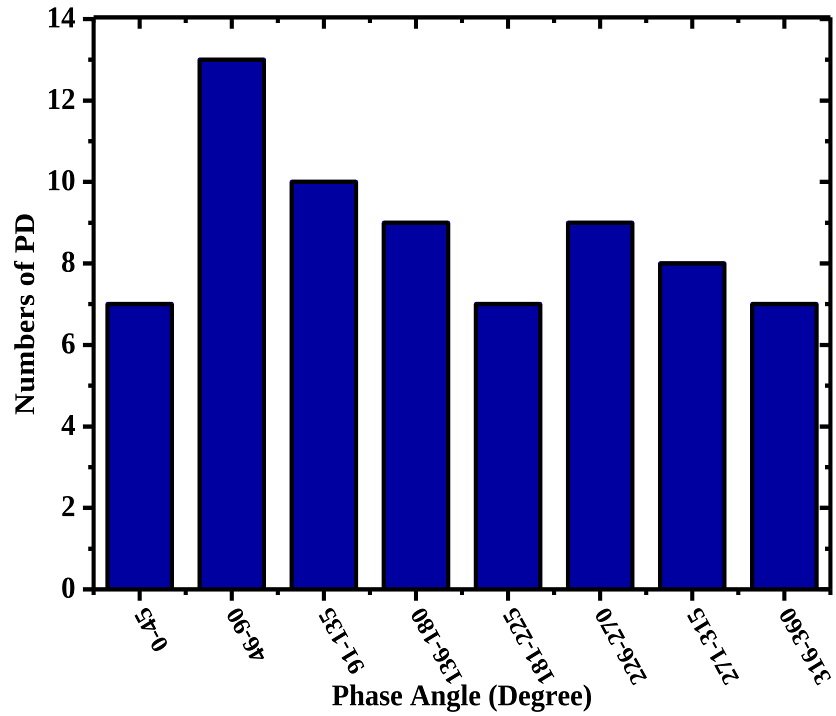

Figure 4.8.The simulated PD pulse found at positive& negative half cycle an applied high voltage of 5 kV

Further an analysis has been made for presence of PD pulses over a total measuring period under different applied voltage varying from 5-30 kV. In this study phase resolve technique has applied for finding the number of PD pulses present in different applied voltage. The total phase angle is divided into eight section having 45˚ phase angle each. It is observed that, the number of PD pulse appeared in the each section is not fixed as the PD is the random phenomenon. In this Fig. 4.9 the PD pulses appeared in the different phase angle of different applied voltage is randomly distributed. As the PD phenomena random in nature, the presences of number of PD pulses are not constant.

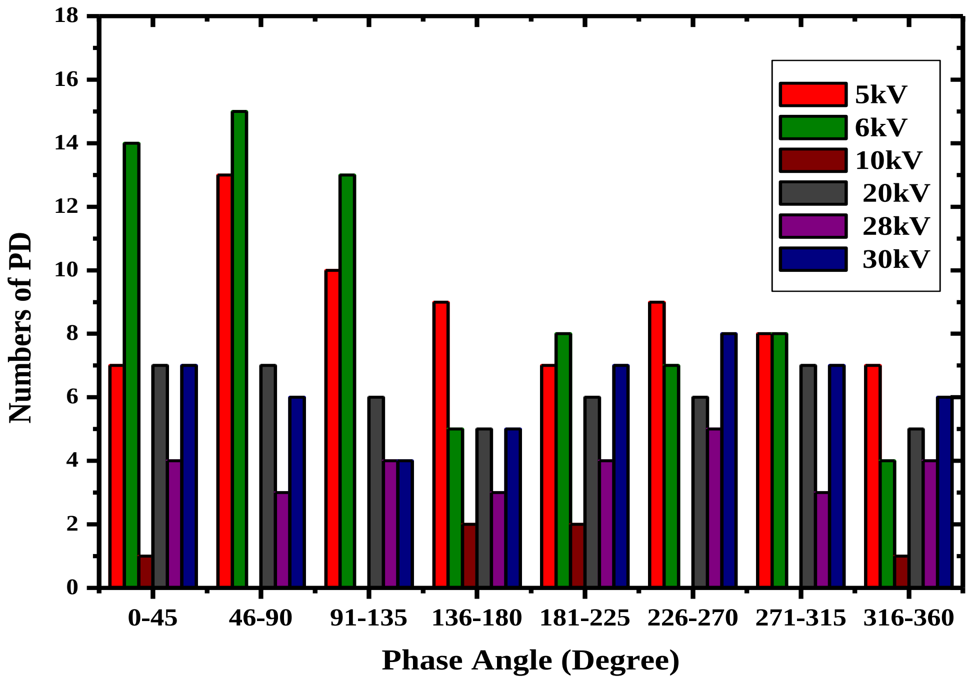

Figure 4.9.The simulated PD pulse found at positive & negative half cycle of different applied voltage

Another analysis has been made for finding out the frequency content of the observed PD pulse which is presented in Fig. 4.10. It shows that the frequency plot of the observed PD pulse with applied voltage of 5 kV. It is observed that the frequency is varies in the range of 1.5 kHz to 20 kHz. As the PD phenomenon is the random in nature so the frequency appears for this PD pulse is also fluctuating in nature. It is also observed that the maximum amplitude of the frequency of the same PD pulse is appears at 5 kHz, 8 kHz and 125 kHz which is shown in Fig. 4.10.

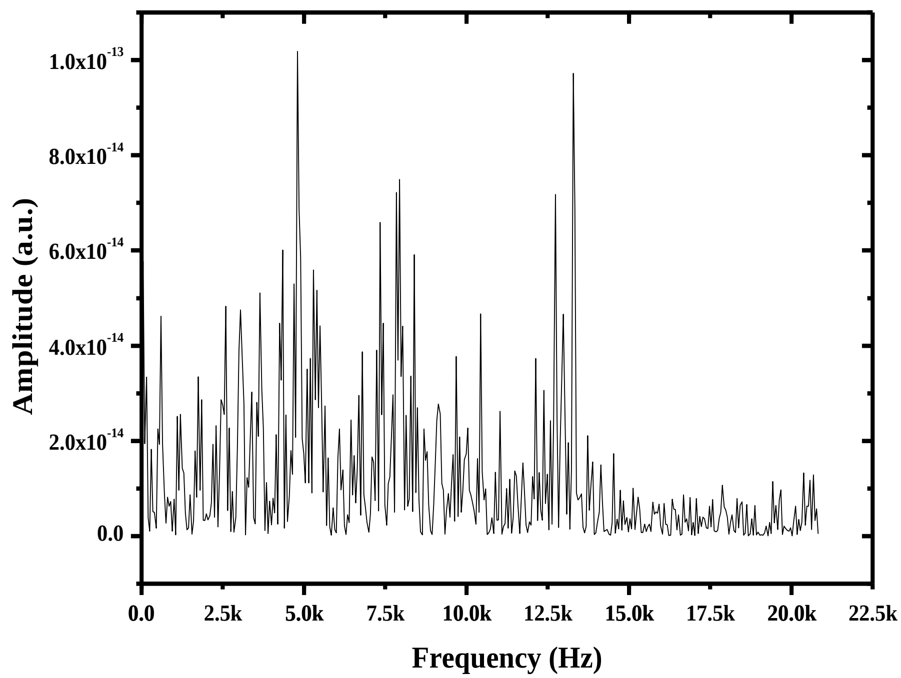

Figure 4.10. Frequency plot of observed PD pulse at 5 kV applied voltage

In this work, an increasing voltage of 0-30 kV is applied between the void models to observe the wide range of the PD activity inside the solid insulation. It is also observed from the Fig. 4.11 that the maximum amplitude of the PD is the function of the applied voltage. As the PD is random phenomenon the appearance of maximum amplitude of such PD signal is also changes over a cycle of applied voltage. The maximum amplitude is varies in the range from 2.09×10^{-5} - 1.5×10^{-4} V with the application of the high voltage range of 5-30 kV which is depicted in Table 5. It is clear that with the increase of the high voltage the amplitude of the PD is also increased.

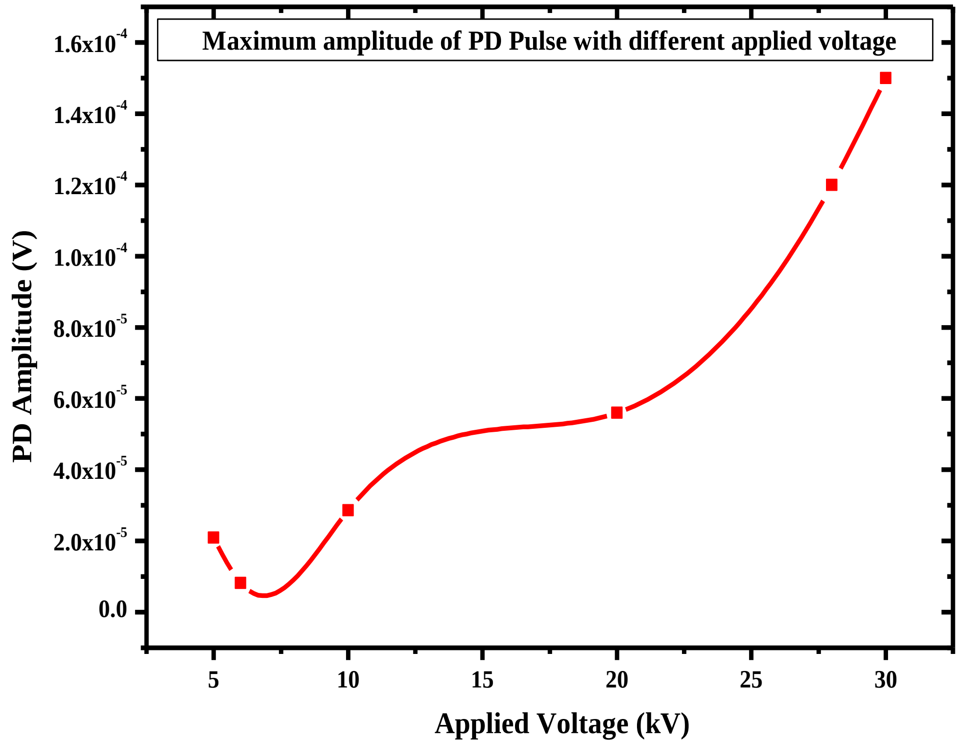

Figure 4.11. Variation of maximum PD amplitude with different applied voltage

TABLE-V

MAXIMUM AMPLITUDE VARIATION OF PD PULSE WITH DIFFERENT APPLIED VOLTAGE

Sl. No.	Applied voltage (kV)	PD amplitude (V)
1	5	2.09×10^{-5}
2	6	8.15×10^{-6}
3	10	2.86×10^{-5}
4	20	5.6×10^{-5}
5	28	1.2×10^{-4}
6	30	1.5×10^{-4}

On the otherhand to observe the charecteristics of the PD pulse an analysis has taken for observing the pulse rise time, fall time and its pulse width for 5 kV applied voltage. The PD pulses which have maximum amplitudes are taken for calculating rise time, fall time and its pulse width which is shown in Fig. 4.12. Four numbers of PD pulse has been taken for calculatng rise time (t_r), fall time (t_f) and pulse width for bth positive as well as for negative half cycle for study of the PD characteristics which are shown in Fig. 4.13 and Fig. 4.15 respectively. The detail of the PD pulses which have been considered for analysis are presented sequentially in the Table 6 and Table 7 respectively. In this work, the rise time and fall time of each PD pulse are calculated for observed voltage impulse of positive as well as negative half cycle with the application of 5 kV applied voltage. It is observed that rise time and fall time of the PD pulse are in order of micro-second in both positive half as well as negative half cycle.

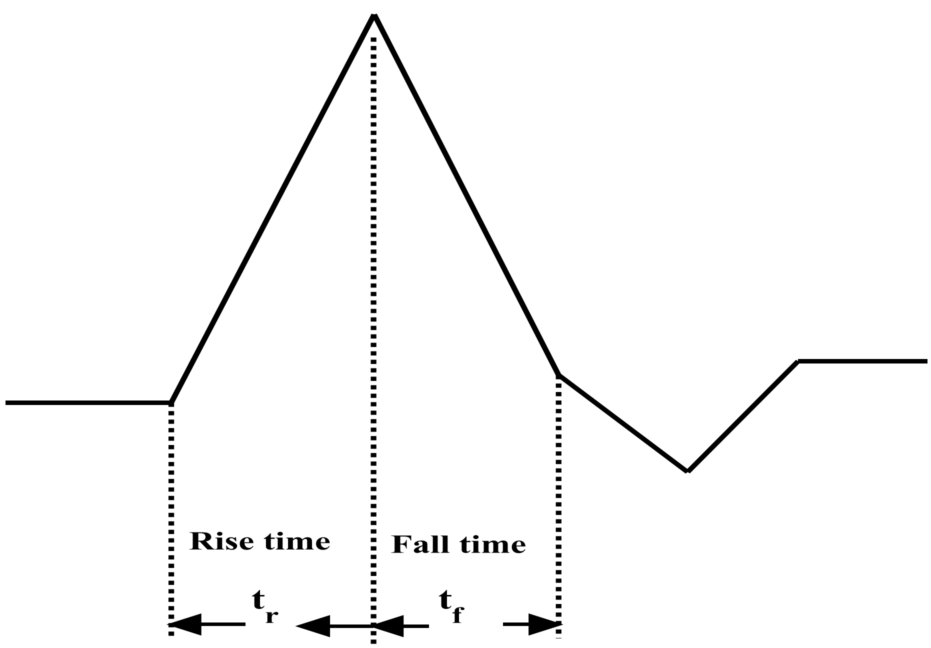

Figure 4.12. Rise time, fall time of a PD pulse

TABLE-VI

RISE TIME AND FALL TIME OF PD PULSE AT 5 kV APPLIED VOLTAGE
FOR POSITIVE HALF CYCLE

Pulse No.	Duration of Rise time (sec)	Rise time (µsec)	Duration of Fall time (sec)	Fall time (µsec)	Pulse width (µsec)
1	0.002966-0.003006	40	0.003006-0.003033	27	67
2	0.004875-0.004918	43	0.004918-0.004942	24	67
3	0.005255-0.005298	43	0.005298-0.005323	25	68
4	0.006010-0.006055	45	0.006055-0.006078	23	68

In positive half cycle appearnce of the total number of pulse is twenty five. Four numbers of PD pulse are taken for calculation of rise time ,fall time and pulse width. The time variation of those pulses are in the range of 0.002966-0.006055 sec. The pulses which are considering for observation is presented clearly in Fig.4.13. The calculated rise time, fall time and its pulse width are depicted in Table 6. It is observed from the Table 6, 7 that the PD pulses are having rise time, fall time and pulse width is in the range of few micro-second. In positive half cycle rise time is nearly about 43-45 µsec and fall time is nearly 23-27 µsec.

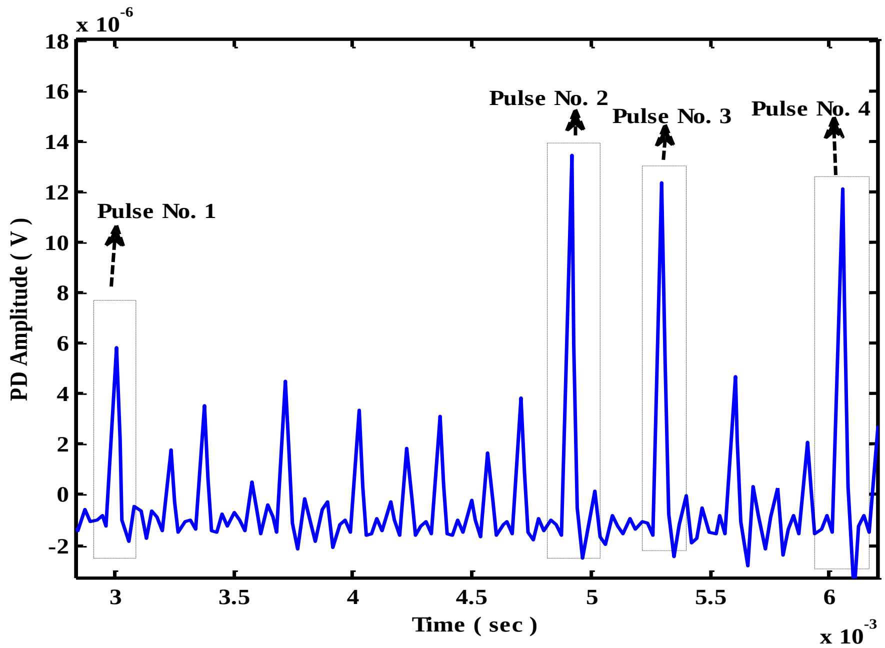

Figure 4.13. Rise time, fall time of observed four number of PD pulse for positive half cycle

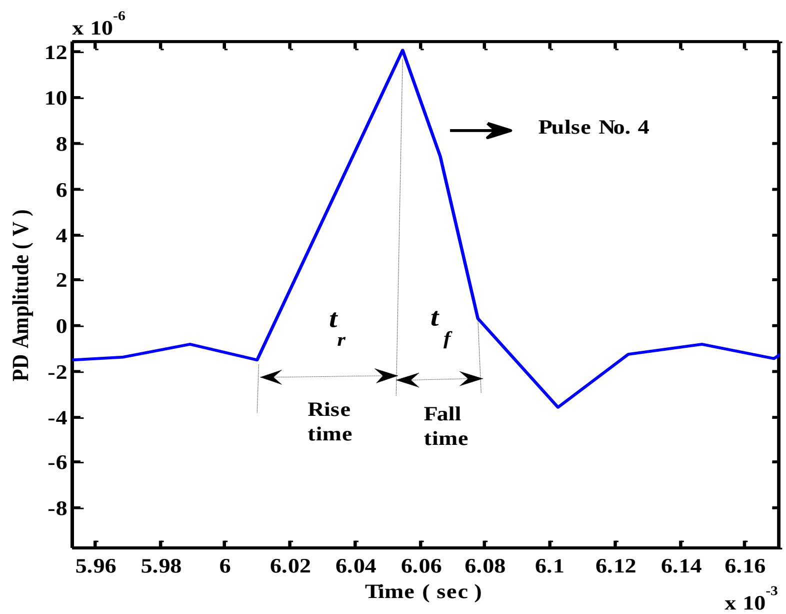

Figure 4.14. Rise time, fall time of observed PD pulse No.4 for positive half cycle

The pulse which is having maximum pulse width is shown in Fig. 4.14. The rise time duration of the measured PD pulse is from 0.006010-0.006078 sec. The calculated rise time of the same PD pulse is 0.000045sec i.e., 45 micro-second. The fall time duration of the measured PD pulse is 0.006055-0.006078 sec. The calculated fall time is 0.000023 sec i.e., 23 micro-second. The pulse width of the measured PD pulse is the addition of rise time and fall time i.e. 68 micro-second.

Further analysis has also done for calculating the rise time and fall time for negative half cycle of the applied voltage. The number of appearance voltage impulse in negative half cycle of of 5 kV.

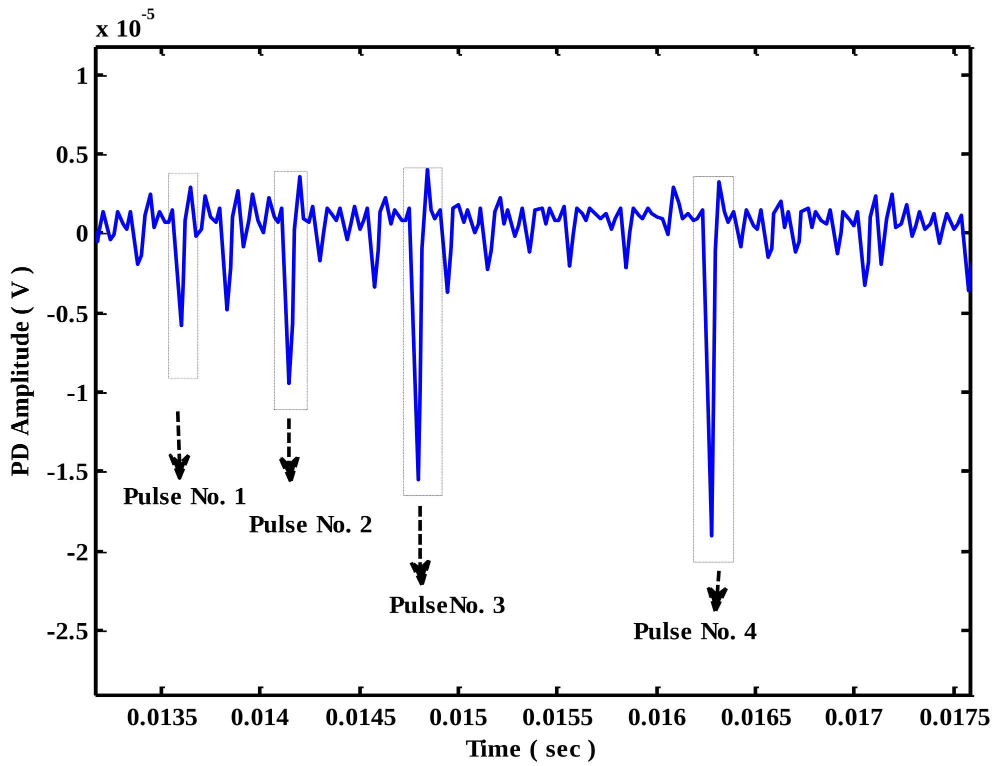

Figure 4.15. Rise time, fall time of observed four number of PD pulse for negative half cycle

applied voltage is thirty two (32). Four numbers of pulse are taken for calculation of rise time, fall time and pulse width of those pulse. The PD pulses which are considered for analysis is presented clearly in Fig.4.15. The calculated rise time, fall time and its pulse width are depicted in Table 7. The time variation of those pulses are from 0.01356-0.01628 sec which is shown in Fig.4.15.

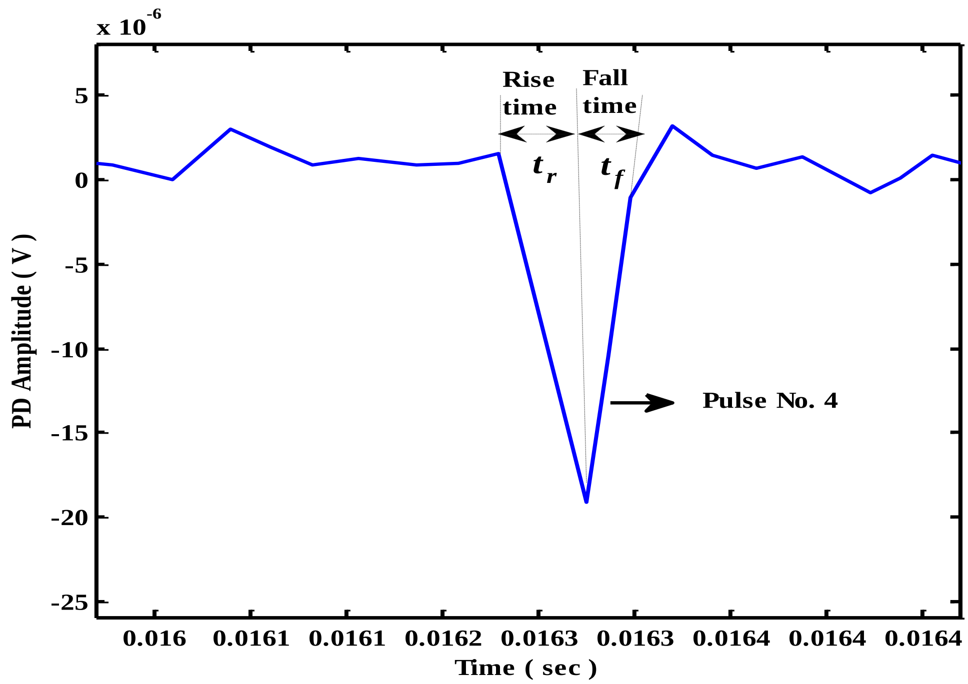

Figure 4.16. Rise time, fall time of observed PD pulse No. 4 for negative half cycle

TABLE-VII

RISE TIME AND FALL TIME OF PD PULSE AT 5 kV APPLIED VOLTAGE FOR NEGATIVE HALF CYCLE

Pulse No.	**Duration of Rise time (sec)**	**Rise time (μsec)**	**Duration of Fall time (sec)**	**Fall time (μsec)**	**Pulse width (μsec)**
1	0.01356-0.01360	40	0.01360-0.01362	20	60
2	0.01411-0.01415	40	0.01415-0.01417	20	60
3	0.01475-0.01479	40	0.01479-0.01482	30	70
4	0.01623-0.01628	50	0.01628-0.01630	20	70

It has been observed that the PD pulses are having rise time, fall time and pulse width is in terms of micro-second. In negative half cycle rise time is nearly about 40-50 µsec and fall time is nearly 20-30 µsec. The pulse which is having maximum pulse width is shown in Fig. 4.16. The duration of that pulse is from 0.01623-0.01630 sec. The pulse rises from at 0.01623 sec and ends at 0.006028 sec.

The calculated rise time of the 4^{th} PD pulse is 0.000050 sec i.e., 50 micro-second. The duration of fall time is 0.01628-0.01630 sec. The calculated fall time is 0.000020 sec i.e.20 micro-second. The pulse width of that pulse is addition of rise time and fall time i.e. 70 micro-second. It has been studied that observed PD signal pulse occurance in negative half cycle has grater rise time and grater pulse width than positive half cycle.

CHAPTER-5

CONCLUSION

AND

SCOPE FOR FUTURE WORK

Chapter-5

Conclusions and Scope for Future work

5.1. CONCLUSION

Partial discharges are a major source of insulation failure in high voltage power system which needs to be monitored continuously to avoid the incipient failure in the power system network. To understand the PD activity inside the solid insulation a MATLAB based simulink model has been developed in this work. The PD activity inside the solid insulation is highly depends on the entire geometry of the void presence inside the solid insulation model (epoxide resin sample). In addition, PD is increases with the increase of applied voltage inside the solid insulation. In this study an efforts have been made to investigate the maximum PD magnitude, number of PDs and number of other PD related parameters like PD distribution, frequency content of obtained PD pulse by using phase resolve partial discharge (PRPD) measurement technique. Based on the developed SIMULINK model and calulated parameters used for epoxide resin sample, the charactericstic of PDs has been studied. This study will ensure the power engineers to predict the quality of the insulation used for high voltage power equipment. The present work is to be extended for further study in different high voltage power equipment such as current transformer (CT), potential transformer (PT), switch gear and circuit breaker.

5.2. SCOPE FOR FUTURE WORK

- A different type of void model has to be developed to investigate the performance characteristic of PD inside the different dielectric medium.
- Detection of the partial discharge activity inside the HV power equipment with advance technology using different detection method which helps the early diagnosis of such high voltage power equipment for their increases of life time as well as the reliable operation.
- Frequency analysis of partial discharges using the developed model.
- On-line monitoring of the power equipment using the developed model.

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REFERENCE

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